

APPENDIX I

San Joaquin River diversion data for 2002 : Patterson Irrigation District and West Stanislaus Irrigation District

I.1 Objective

This report updates the diversion data in the Quinn and Tulloch Final Report (Quinn and Tulloch, 2002) to include all of the 2002 pumping data. This information was gathered from telemetered flow and water quality monitoring stations that were completed with partial support from the CALFED-sponsored San Joaquin River Low Dissolved Oxygen Project .

I.2 Background

In the Final Project Report to CALFED entitled “San Joaquin River diversion data assimilation, drainage estimation and installation of diversion monitoring stations, (Quinn and Tulloch, 2002)” the authors provided analysis which showed the importance of accurate estimation of river diversions to the development of a mass balance of algal loads from the upper watersheds. Algal loads are diverted from the San Joaquin River along with river water – only a small portion of this water is returned directly to the river. In some water districts such as Patterson Irrigation District, facilities have been completed to eliminate all surface water returns to the San Joaquin River. When diverted river water is applied to land to irrigate crops the algae is filtered by the soil and becomes an organic amendment to the soil. Deep percolating irrigation water may be intercepted by drainage ditches or become part of the regional groundwater system that flows towards the San Joaquin River. In the case of water intercepted directly by surface drainage ditches and of subsurface tile drains discharging to surface drainage ditches there is opportunity for algal growth depending on the length of time the drainage water remains in the channel. On the west side of the San Joaquin Valley between Highway 140 and Vernalis, the travel times between field and the SJR are typically short – as a result of the short flow paths to the river. As a consequence it is anticipated that river diversions in this reach of the river will have a greater impact on algal loading than drainage return flows.

There are approximately 41 riparian and appropriative diverters of San Joaquin River water between Lander Avenue and Vernalis. A boat survey conducted during 2001 produced a count of over 100 individual lift pumps along the levee in the reach of the River between Vernalis and the Stockton Deep Water Ship Channel (DWSC). The major river diverters in the reach between Lander Avenue and Vernalis are Patterson Irrigation District (PID), West Stanislaus Irrigation District (WSID)and El Solyo Water District (ESWD). As part of the 2001 CALFED study monitoring equipment was installed and maintained in the first lift Canals of both the PID and WSID. This monitoring equipment and the arrangements made with both these water districts for data access provided CALFED with real-time data for San Joaquin River diversions into these districts. This capability is crucial for future modeling purposes.

West Stanislaus Irrigation District was formed in 1920 – the first water deliveries to the District were made in 1929. Water deliveries have increased from 12,000 acre-feet the first year to a maximum of 113,000 acre-feet in 1984. Water from the San Joaquin River is conveyed through a mile-long unlined gravity canal to the first pumping plant where water is lifted 35 ft into the

concrete lined main canal. A total of six pumping plants lift water to an elevation of 165 ft above sea level. Water is diverted from the main canal to laterals that run north and south. In 1929 all water supply to the District was diverted from the San Joaquin River. After the construction of Friant Dam and the diversion of San Joaquin River water to the southern San Joaquin Valley the quality of water diverted from the SJR declined. Litigation from west-side riparian water districts resulted in the provision of federal water deliveries from the Delta to offset these water quality problems. In 1953 the district signed a contract for 20,000 acre-feet of water – this was increased to 50,000 acre-feet in 1976. The Water District has diverted up to 66,000 acre-feet from turnouts at mile 31.31 and 38.13 along the Delta-Mentota Canal. The District irrigates approximately 22,500 acres of cropland through 84 miles of laterals and sublaterals. Although Delta water typically is of better quality than San Joaquin River water the District typically diverts its maximum allocation from the River, largely on account of the lower cost. This policy is true also for Patterson ID and Banta Carbona ID.

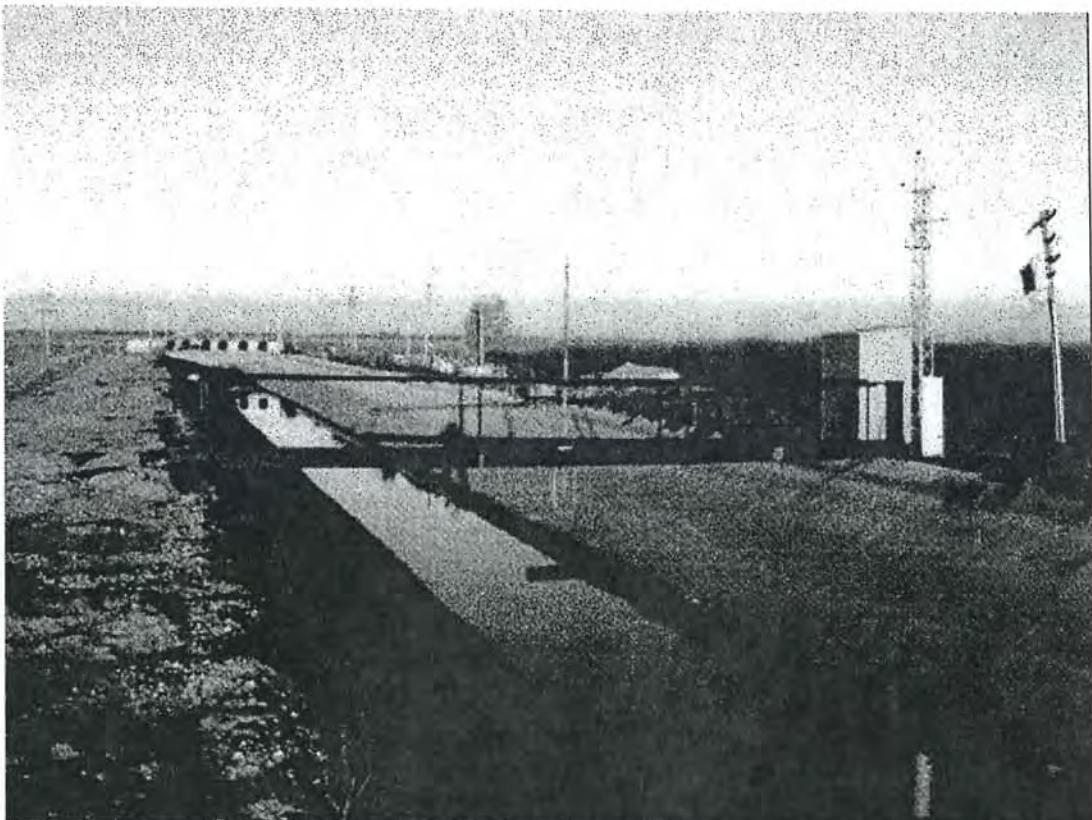


Figure I-1. Flow and water quality monitoring station at the West Stanislaus Irrigation District.

Patterson Irrigation District was organized much later than West Stanislaus Irrigation District, in 1955. The District has pre-1914 appropriative water rights that entitles it to pump water from the San Joaquin River from its inception as the Patterson Land Company in 1909. In 1967 the District entered into a long term contract with the Bureau of Reclamation for 22,500 acre-ft as compensation for the loss of high quality San Joaquin River water. The area of the water district

Congress of the United States
House of Representatives
Washington, DC 20515

February 2, 2009

The Honorable Ken Salazar
Secretary
Department of the Interior
1849 C Street, N.W.
Washington DC 20240

Dear Secretary Salazar:

As you are probably aware, California is experiencing its third consecutive year of extremely dry conditions, setting the stage for what experts believe may be among the worst droughts in California's history. We are writing to request your immediate attention to California's water supply crisis.

California reservoirs are dangerously low. Unless the months of February and March bring above average rain and snowfall, the U.S. Bureau of Reclamation is expected to provide no Central Valley Project water to South-of-Delta agricultural service contractors. A zero allocation is unprecedented in the history of the CVP. Last year, over 200,000 acres of some of the world's most productive farmland were fallowed, and this number is expected to increase substantially this year. A zero water supply will cripple communities that rely upon federal and state project water deliveries, and West-side agriculture in the San Joaquin Valley will be especially hard hit.

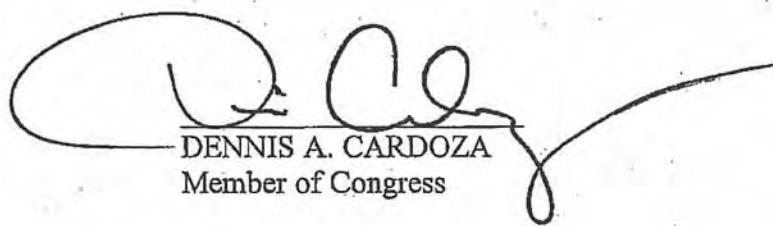
On top of the driest conditions on record, the water supply outlook is further exacerbated by the "regulatory drought" that has resulted from agency regulatory actions. The Endangered Species Act in particular has proven to be a regulatory hammer, preventing water conveyance, transfers and storage, even when water supplies have been plentiful. In 2007 and 2008, U.S. District Court Judge Oliver Wanger issued separate rulings pertaining to biological opinions to protect Delta smelt and salmonid species. In connection with the decision related to the Delta smelt, Judge Wanger ordered significant pumping curtailments, which reduced water deliveries. These cuts were in addition to the many previous cuts that had already been imposed, including the Bay Delta Accord, the Central Valley Project Improvement Act and other actions. Judge Wanger's order related to the Delta smelt expired upon issuance of a new biological opinion for Delta smelt, but that new opinion included alternatives that are more draconian than the measures ordered by the District Court. Moreover, as a result of Judge Wanger's opinion related to salmonid species, NOAA Fisheries will release a new biological opinion, and it is anticipated that this new opinion will further restrict operations of the Central Valley Project and the State Water Project.

It is crucial that the Department of the Interior and its agencies--- the Fish and Wildlife Service, the Bureau of Reclamation--- and the NOAA Fisheries exercise the maximum flexibility in the operations of the Central Valley Project and the State Water Project in such a way as to maximize water allocations, obtain supplemental water supplies, and expedite water transfers. The development and implementation of the biological opinions required under the Wanger decisions will be the Administration's first test of flexible implementation. Furthermore, it is crucial that the Administration be fully engaged in the Bay Delta Conservation Plan process initiated by the State of California, with the goal toward developing a plan for the state of California that increases water supply reliability, environmental enhancement, water quality and flood protection.

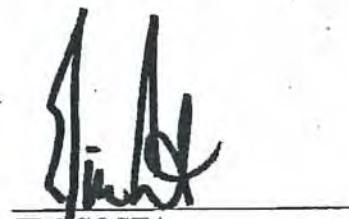
We would like to meet with you as soon as possible regarding California's water supply crisis. We also request that you visit areas of California affected by the drought in order to see firsthand the impacts of this crisis and to meet with farmers, farm workers, and members of communities devastated by the water supply shortages. The end desire is to discuss ways in which the Department can provide flexibility in the operations of the projects as well as ways in which the Administration can provide leadership in the development of a comprehensive water plan for the entire state.

The coming days and months will be challenging at best, and we are committed to working with the federal and state administrations on both immediate and long-term solutions. Your timely attention to these matters is greatly appreciated.

Sincerely,



DENNIS A. CARDOZA
Member of Congress



JIM COSTA
Member of Congress

DEPARTMENT OF THE INTERIOR**Bureau of Reclamation****Grassland Bypass Project, 2010–2019, Fresno and Merced Counties, CA**

AGENCY: Bureau of Reclamation, Interior.

ACTION: Notice of Availability and Notice of Public Hearing for the joint Draft Environmental Impact Statement/Environmental Impact Report (Draft EIS/EIR).

SUMMARY: The Bureau of Reclamation (Reclamation) is the National Environmental Policy Act (NEPA) Federal lead agency and the San Luis and Delta-Mendota Water Authority (Authority) is the California Environmental Quality Act (CEQA) State lead agency. Together, these agencies have made available for public review and comment the Draft EIS/EIR.

The joint Draft EIS/EIR evaluates the effects of continuing the Grassland Bypass Project until December 31, 2019 (Project). The actions analyzed in the Draft EIS/EIR include continued use of the Grassland Bypass Channel and a 28-mile segment of the San Luis Drain (Drain); continued discharges to Mud Slough until December 31, 2019; management of accumulated sediments within the Drain segment; ongoing use and development of areas utilized for application of subsurface drainage on salt tolerant crops; and programmatic consideration of future phases of the treatment and disposal program.

DATES: A public hearing will be held on Tuesday, February 10, 2009 from 1:30 to 3:30 p.m. to provide the public an opportunity to comment on the Draft EIS/EIR. Written comments will also be accepted at the public hearing.

Submit written comments on the Draft EIS/EIR on or before March 16, 2009.

ADDRESSES: The public hearing location is the San Luis & Delta-Mendota Water Authority, Boardroom, 842 Sixth Street, Suite 7, Los Banos, CA.

Written comments on the Draft EIS/EIR should be addressed to Ms. Judi Tapia, Bureau of Reclamation, 1243 'N' Street, Fresno, CA 93721–1831 or Mr. Joseph C. McGahan, Drainage Coordinator, San Luis & Delta-Mendota Water Authority, P.O. Box 2157, Los Banos, CA 93635, fax 209–826–9698, e-mail: jmcgahan@summerseng.com.

Copies of the draft document may be requested from Ms. Judi Tapia at the above address, by calling 559–487–5138, TDD 559–487–5933, or at jtapia@mp.usbr.gov. Copies may also be requested from Mr. Joseph C. McGahan, at the above address. The Draft EIS/EIR

is also accessible from the following Web sites: <http://www.usbr.gov/mp/nepa/index.cfm>. See **SUPPLEMENTARY INFORMATION** section for locations where copies of the Draft EIS/EIR are available. **FOR FURTHER INFORMATION CONTACT:** Ms. Judi Tapia, Bureau of Reclamation or Mr. Joseph C. McGahan, San Luis & Delta-Mendota Water Authority at the phone numbers or e-mail addresses above.

SUPPLEMENTARY INFORMATION: The Project and the Grassland Drainage Area are located in Merced and Fresno Counties in the Central Valley of California. Prior to 1996 when the interim project was implemented, subsurface agricultural drainage water was conveyed through channels used to deliver water to wetland habitat areas which limited Reclamation's ability to deliver fresh water to the wetlands. The Project now consolidates subsurface drainage flows on a regional basis (from the 97,400-acre Grassland Drainage Area), applies the drainage to salt tolerant crops to reduce the volume, utilizes a 4-mile channel to place it into the Drain at a point near Russell Avenue (Milepost 105.72, Check 19) and then utilizes a 28-mile segment of the Drain to convey the remaining drainage flows around wetland habitat areas and after which it is discharged to Mud Slough and subsequently reaches the San Joaquin River.

The original Grassland Bypass Project was implemented in November 1995 through an "Agreement for Use of the San Luis Drain" (Agreement No. 6–07–20–w1319) between Reclamation and the Authority. A Finding of No Significant Impact (FONSI No. 96–1–MP) was adopted by Reclamation for the original project, and environmental commitments set forth in the FONSI were made an integral component of the initial Use Agreement. The Use Agreement and its renewal in 1999 allowed for use of the Drain for a 5-year period that concluded September 30, 2001. A new Use Agreement (Agreement No. 01–WC–20–2075) was completed on September 28, 2001 for the period through December 31, 2009.

The original Grassland Bypass Project's use of the Drain was only authorized until December 31, 2009, and subsurface drainage flows discharged to Mud Slough (North) were to have met water quality objectives by October 1, 2010 as required by the Regional Water Quality Control Board, Central Valley Region's (CVRWQCB) 1998 Water Quality Control Plan (Basin Plan) for the Sacramento River and San Joaquin River Basins. However, delay in the acquisition of funding has delayed

the development and availability of treatment and disposal technology to reduce selenium loads to meet that 2010 deadline. It is anticipated that the proposed extension would allow enough time to acquire funds and develop feasible treatment technology in order to meet the Basin Plan objectives and Waste Discharge Requirements.

In order to continue to discharge into Mud Slough (North) in the State's China Island Wildlife Area, the Authority would need to extend or amend a Memorandum of Understanding with the California Department of Fish and Game, Reclamation would need to extend the Use Agreement with the Authority for the continued use of the Drain after 2009, the CVRWQCB would need to revise their Basin Plan objectives for 2010 and amend the existing Waste Discharge Requirements in order to allow for anticipated drainage discharge into Mud Slough, and Reclamation and the Authority would need to remove existing and future sediments from the affected portion of the Drain.

The actions analyzed in the Draft EIS/EIR include continued use of the Grassland Bypass Channel and a 28-mile segment of the Drain; continued discharges to Mud Slough until December 31, 2019; management of accumulated sediments within that Drain segment; ongoing use and development of areas utilized for application of subsurface drainage on salt tolerant crops; and programmatic consideration of future phases of the treatment and disposal program. The Draft EIS/EIR considers the direct, indirect, and cumulative effects on the physical, natural, and human environment that may result from the Project actions above. The Draft EIS/EIR addresses potentially significant environmental issues and recommends adequate and feasible mitigation measures to reduce or eliminate significant environmental impacts, where possible. No project/no action alternative and one other action alternative are addressed.

Copies of the Draft EIS/EIR are available for public review at the following locations:

- Bureau of Reclamation, South-Central California Area Office, 1243 'N' Street, Fresno, CA 93721–1831
- U.S. Bureau of Reclamation, Mid-Pacific Regional Office Library, 2800 Cottage Way, Sacramento, CA 95825
- San Luis & Delta-Mendota Water Authority, 842 Sixth Street, Los Banos, CA 93635
- San Francisco Public Library, 100 Larkin Street, San Francisco, CA 94012

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- University of California-Davis, Shields Library, Documents Department, 100 NW Quad University of California, Davis, CA 95616-5292
- Merced County Public Library, 1312 South 7th Street, Los Banos, CA 93635-4757
- Fresno County Public Library Government Publications, 2420 Mariposa Street, Fresno, CA 93721-2204
- Stanislaus County Library, 1500 I Street, Modesto, CA 95354
- Resources Agency Library, 1416 Ninth Street, Suite 117, Sacramento, CA 95814-5510
- California State Library, 914 Capitol Mall, Suite E-29, Sacramento, CA 95814-4802
- University of California, Berkeley, Water Resources Archive, 410 O'Brien Hall, Berkeley, CA 94720-1718

If special accommodation is required, please contact Susan Mussett at 209-826-9696 or susan.mussett@sldmwa.org by January 30, 2009 to enable the Authority to secure the needed services.

Before including your name, address, phone number, e-mail address, or other personal identifying information in your comment, you should be aware that your entire comment—including your personal identifying information—may be made publicly available at any time. While you can ask us in your comment to withhold your personal identifying information from public review, we cannot guarantee that we will be able to do so.

Dated: December 11, 2008.

John F. Davis,
Deputy Regional Director, Mid-Pacific Region.
[FR Doc. E9-723 Filed 1-14-09; 8:45 am]
BILLING CODE 4310-MN-P

INTERNATIONAL TRADE COMMISSION

[Investigation No. 731-TA-1012 (Review)]

Certain Frozen Fish Fillets From Vietnam

AGENCY: United States International Trade Commission.

ACTION: Scheduling of a full five-year review concerning the antidumping duty order on certain frozen fish fillets from Vietnam.

SUMMARY: The Commission hereby gives notice of the scheduling of a full review pursuant to section 751(c)(5) of the Tariff Act of 1930 (19 U.S.C. 1675(c)(5)) (the Act) to determine whether revocation of the antidumping duty order on certain frozen fish fillets from Vietnam would be likely to lead to

continuation or recurrence of material injury within a reasonably foreseeable time. For further information concerning the conduct of this review and rules of general application, consult the Commission's Rules of Practice and Procedure, part 201, subparts A through E (19 CFR part 201), and part 207, subparts A, D, E, and F (19 CFR part 207).

DATES: Effective Date: January 9, 2009.

FOR FURTHER INFORMATION CONTACT: Russell Duncan (202-708-4727, russell.duncan@usitc.gov), Office of Investigations, U.S. International Trade Commission, 500 E Street, SW., Washington, DC 20436. Hearing-impaired persons can obtain information on this matter by contacting the Commission's TDD terminal on 202-205-1810. Persons with mobility impairments who will need special assistance in gaining access to the Commission should contact the Office of the Secretary at 202-205-2000. General information concerning the Commission may also be obtained by accessing its Internet server (<http://www.usitc.gov>). The public record for this review may be viewed on the Commission's electronic docket (EDIS) at <http://edis.usitc.gov>.

SUPPLEMENTARY INFORMATION:

Background.—On October 6, 2008, the Commission determined that responses to its notice of institution of the subject five-year review were such that a full review pursuant to section 751(c)(5) of the Act should proceed (73 FR 62318, Monday, October 20, 2008). A record of the Commissioners' votes, the Commission's statement on adequacy, and any individual Commissioner's statements are available from the Office of the Secretary and at the Commission's Web site.

Participation in the review and public service list.—Persons, including industrial users of the subject merchandise and, if the merchandise is sold at the retail level, representative consumer organizations, wishing to participate in this review as parties must file an entry of appearance with the Secretary to the Commission, as provided in section 201.11 of the Commission's rules, by 45 days after publication of this notice. A party that filed a notice of appearance following publication of the Commission's notice of institution of the review need not file an additional notice of appearance. The Secretary will maintain a public service list containing the names and addresses of all persons, or their representatives, who are parties to the review.

Limited disclosure of business proprietary information (BPI) under an

administrative protective order (APO) and BPI service list.—Pursuant to section 207.7(a) of the Commission's rules, the Secretary will make BPI gathered in this review available to authorized applicants under the APO issued in the review, provided that the application is made by 45 days after publication of this notice. Authorized applicants must represent interested parties, as defined by 19 U.S.C. 1677(9), who are parties to the review. A party granted access to BPI following publication of the Commission's notice of institution of the review need not reapply for such access. A separate service list will be maintained by the Secretary for those parties authorized to receive BPI under the APO.

Staff report.—The prehearing staff report in the review will be placed in the nonpublic record on April 16, 2009, and a public version will be issued thereafter, pursuant to section 207.64 of the Commission's rules.

Hearing.—The Commission will hold a hearing in connection with the review beginning at 9:30 a.m. on May 6, 2009, at the U.S. International Trade Commission Building. Requests to appear at the hearing should be filed in writing with the Secretary to the Commission on or before May 1, 2009. A nonparty who has testimony that may aid the Commission's deliberations may request permission to present a short statement at the hearing. All parties and nonparties desiring to appear at the hearing and make oral presentations should attend a prehearing conference to be held at 9:30 a.m. on May 4, 2009, at the U.S. International Trade Commission Building. Oral testimony and written materials to be submitted at the public hearing are governed by sections 201.6(b)(2), 201.13(f), 207.24, and 207.66 of the Commission's rules. Parties must submit any request to present a portion of their hearing testimony *in camera* no later than 7 business days prior to the date of the hearing.

Written submissions.—Each party to the review may submit a prehearing brief to the Commission. Prehearing briefs must conform with the provisions of section 207.65 of the Commission's rules; the deadline for filing is April 27, 2009. Parties may also file written testimony in connection with their presentation at the hearing, as provided in section 207.24 of the Commission's rules, and posthearing briefs, which must conform with the provisions of section 207.67 of the Commission's rules. The deadline for filing posthearing briefs is May 15, 2009; witness testimony must be filed no later than two days before the hearing. In

Prediction of optimal safe ground water yield and land subsidence in the Los Banos-Kettleman City area, California, using a calibrated numerical simulation model

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Received 5 January 2000; revised 10 October 2000; accepted 11 October 2000

Abstract

Land subsidence caused by the excessive use of ground water resources has traditionally caused serious and costly damage to the Los Banos-Kettleman City area of California's San Joaquin Valley. Although the arrival of surface water from the Central Valley Project has reduced subsidence in recent decades, the growing instability of surface water supplies has refocused attention on the future of land subsidence in the region. This paper uses integrated numerical ground water and land subsidence models to simulate land subsidence caused by ground water overdraft. The simulation model is calibrated using observed data from 1972 to 1998, and the responsiveness of the model to variations in subsidence parameters are analyzed through a sensitivity analysis. A probable future drought scenario is used to evaluate the effect on land subsidence of three management alternatives over the next thirty years. The model reveals that maintaining present practices virtually eliminates unrecoverable land subsidence, but may not be a sustainable alternative because of a growing urban population to the south and concern over the ecological implications of water exportation from the north. The two other proposed management alternatives reduce the dependency on surface water by increasing ground water withdrawal. Land subsidence is confined to tolerable levels in the more moderate of these proposals, while the more aggressive produces significant long-term subsidence. Finally, an optimization model is formulated to determine maximum ground water withdrawal from nine pumping sub-basins without causing irrecoverable subsidence during the forecast period. The optimization model reveals that withdrawal can be increased in certain areas on the eastern side of the study area without causing significant inelastic subsidence. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Land subsidence; Ground water overdraft; Numerical models; Optimization

1. Introduction

California's San Joaquin Valley is one of the most productive and intensely farmed agricultural areas in the world (American Farmland Trust, 1995), contributing billions of dollars to the state's economy and providing jobs and food for the state's growing population. As

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such, providing affordable water for agriculture has traditionally been a high priority for water managers in the region. Prior to the arrival of surface water supplies in the late 1960s, intense abstractions of ground water in excess of natural recharge resulted in land subsidence across the Valley (Ireland et al., 1984). Although the arrival of surface water has reduced land subsidence in recent decades, subsidence remains a pertinent concern due to the tenuous nature of surface water deliveries in the region.

Land subsidence can have several negative economic, social, and technical implications. Problems associated with land subsidence include: (1) changes in ground water and surface water flow patterns (Lofgren, 1979); (2) ground water quality deterioration and salt-water encroachment (Belitz and Phillips, 1995); (3) decline in storage capacity

(Rudolph and Frind, 1991) and restrictions on pumping in land-subsidence prone areas (Ortega-Guerrero et al., 1999); (4) localized flooding (Hua et al., 1993); (5) failure of well casings and changes in channel gradient (Holzer, 1989); and (6) damage to highways, buildings, and other structures (Ireland et al., 1984). Many of these problems have been observed in the San Joaquin Valley (Ireland, 1986).

The main objectives of this paper are: (1) to evaluate the effects of existing and proposed water management plans on land subsidence in the Los Banos-Kettleman City region of the San Joaquin Valley; and (2) to determine the maximum pumping capacity of the basin without causing inelastic compaction over the next thirty years. This will be accomplished through: (1) employment of existing numerical models to simulate ground water flow and

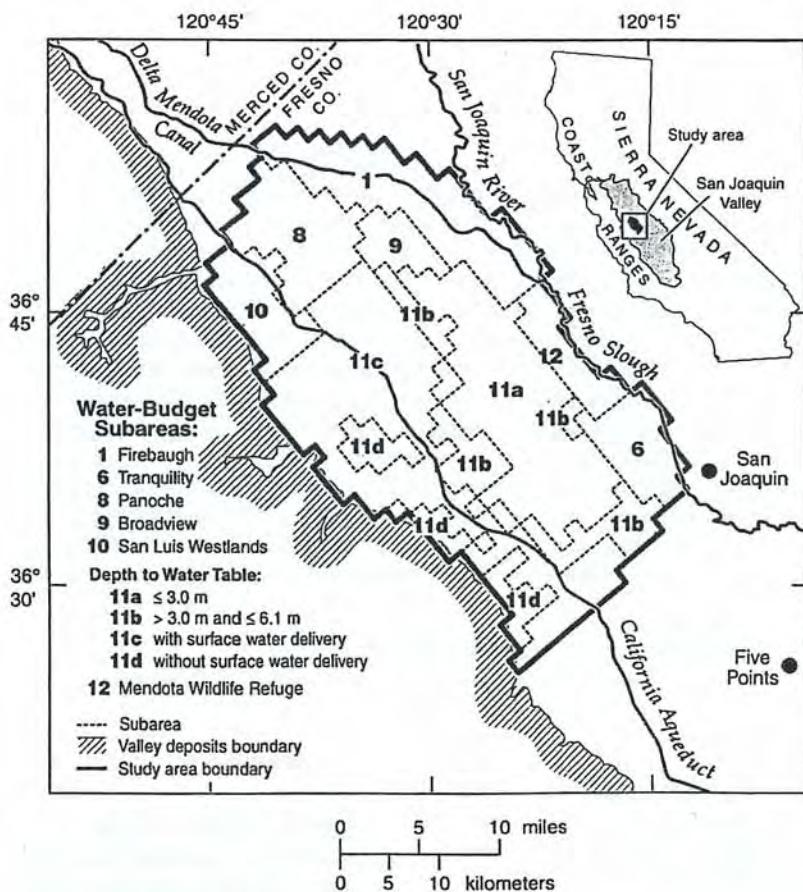


Fig. 1. Location of study area and water budget subareas.

land subsidence in the Los Banos-Kettleman City region; (2) calibration of the models using observed ground water and compaction data for the years 1972–1998; (3) identification of the most influential aquifer parameters and their roles in model calibration; (4) construction of future water availability scenarios; (5) implementation of the calibrated model to estimate future land subsidence for existing and proposed management alternatives; and (6) formulation of an optimization model to determine the maximum ground water withdrawal without causing inelastic compaction.

2. Background

Prior to arrival of surface water supplies in the late 1960s, more than half of the San Joaquin Valley had been exposed to the ill effects of land subsidence (Poland et al., 1975; Ireland et al., 1984). By 1969, subsidence had reached nearly 8.8 m in one location with a total volume of $19.1 \times 10^9 \text{ m}^3$ (Poland, 1981). When the California Aqueduct was completed in the late 1960s, the demand for ground water was reduced substantially. This resulted in a 50–70% decrease in annual subsidence rates by the end of 1971.

*5 times
over 100 ft*

During droughts in 1976–1977 and 1990–1994, ground water supplies were pumped heavily to meet demand as surface water deliveries were reduced. In the Los Banos-Kettleman City area, pumping reached $0.58 \times 10^9 \text{ m}^3$ in 1977 compared to a yearly average of less than $0.12 \times 10^9 \text{ m}^3$ between 1974 and 1976 (Ireland et al., 1984). The result was a return to subsidence rates comparable to those before the arrival of surface water. More recently, the Central Valley Project Improvement Act (CVPIA) has mandated the transfer of $0.99 \times 10^9 \text{ m}^3$ of surface water for environmental uses. Although recent measurements reveal that annual average land subsidence rates have declined over the last three decades, drought and the politically volatile future of surface water in the region maintain land subsidence as a serious concern to local and state water agencies (California Department of Water Resources, 1998b).

3. Study area

Three areas of the San Joaquin Valley exhibit espe-

cially severe subsidence: the Los Banos-Kettleman City area, the Tulare-Wasco area, and the Arvin-Mari-copa area. The area chosen for this research comprises the northern portion of the Los Banos-Kettleman City area. This 1425 km^2 region of western Fresno County (Fig. 1) has been chosen because of the large amount of ground water and land subsidence data available. Additionally, several previous studies have been conducted in the region, providing important insight into several aspects of this research.

3.1. Hydrogeology

The hydrogeology of the Los Banos Kettleman City area was previously documented by Miller et al. (1971) and Belitz and Heimes (1990). The subsurface flow system is divided into upper and lower water-bearing zones, which are separated by the Corcoran Clay Member of the Tulare Formation (Fig. 2). The thickness of the Corcoran Clay Member ranges from 6 to 37 m (Page, 1986) and consists of low-conductivity lacustrine deposits (Johnson et al., 1968).

The unconfined to semi-confined zone above the Corcoran Clay member consists of Coast Range alluvium, Sierran sand, and flood basin deposits. The Coast Range alluvium reaches a thickness of more than 240 m near the western edge of the valley. It is composed of sand and gravel along the stream channels and at the fan heads, and of clay and silt in the distal fan areas (Laudon and Belitz, 1991). The Coast Range alluvium is inter-fingered laterally with the Sierran sand, which consists of well-sorted medium to coarse-grained fluvial sand reaching a thickness of 120–150 m in the valley trough (Miller et al., 1971). Flood-basin deposits, with a thickness of 1.5–11 m, overlie the Sierran sand at the center of the valley (Laudon and Belitz, 1991). The quality of ground water in the upper water-bearing zone is generally poor with high concentrations of calcium, magnesium, and sulfate (with an average total dissolved solids of 3000 mg/l), except near the Fresno Slough (with an average total dissolved solids of around 850 mg/l) (Bull and Miller, 1975).

The lower water-bearing zone is locally less permeable than the upper-water bearing zone. It is also much thicker, ranging from 170 to 750 m (Williamson et al., 1989). It is composed of poorly consolidated flood-basin, deltaic, alluvial-fan, and lacustrine deposits of Tulare formation (Bull and

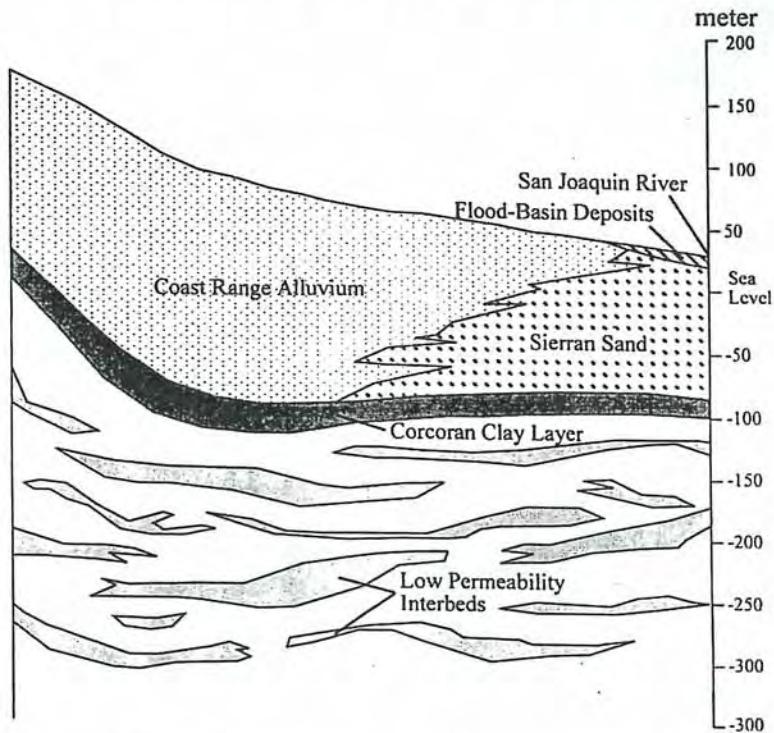


Fig. 2. Schematic hydrogeologic cross-section of the study area (modified from Belitz et al., 1992).

Miller, 1975), characterized by discontinuous clay lenses embodied with sand and gravel deposits. Before surface water supplies were made available to the Los Banos-Kettleman City area through aqueducts and irrigation channels, 75–80% of irrigation water was pumped from the lower water-bearing zone due to its greater thickness and superior water quality (with an average total dissolved solids of 100 mg/l or less) (Bull and Miller, 1975; Ireland et al., 1984).

3.2. Water budget

Gronberg and Belitz (1992) performed an analysis of ground water pumpage, recharge, and irrigation efficiency for the Los Banos-Kettleman City region. The region was divided into nine water-budget subareas based on water district boundaries and depth to water table (Fig. 1). This analysis resulted in two water budgets for the years 1980 and 1984.

Gronberg and Belitz (1992) did not consider drought in their water budget analysis. However,

drought has substantial influence on the rate and magnitude of land subsidence. During normal water years, this paper adopts the pumping rates and spatial distribution between subareas computed by Gronberg and Belitz (1992) for the year 1980 (Table 1). For drought periods, however, ground water pumping rates are calculated as a function of available surface water supplies.

4. Land subsidence model

Land subsidence is modeled using a modular subroutine of MODFLOW (McDonald and Harbaugh, 1988) called the Interbed Storage Package-1 (IBS1) (Leake and Pradic, 1991). The IBS1 package is based on the one-dimensional consolidation theory of Terzaghi (1925). As a load is applied to a saturated, low-conductivity soil, the water towards the middle of the soil is unable to escape and pore water pressure develops. The pressure that remains to support the soil matrix is called residual pore pressure. No

Table 1
Revised water budget for 1980 (modified from Gronberg and Belitz, 1992)

| Subarea | Area (km ²) | Surface water delivery (m/year) | Ground water pumpage (m/year) | Ground water recharge (m/year) |
|--------------------------------|----------------------------|------------------------------------|----------------------------------|-----------------------------------|
| Firebaugh | 189.07 | 0.80 | 0.00 | 0.23 |
| Panoche | 124.32 | 0.76 | 0.00 | 0.29 |
| Broadview | 41.44 | 0.84 | 0.00 | 0.24 |
| Tranquility | 77.70 | 0.77 | 0.09 | 0.26 |
| San Luis | 77.70 | 0.57 | 0.12 | 0.24 |
| Westlands | | | | |
| Depth to water < 3.0 m | 251.23 | 0.58 | 0.12 | 0.14 |
| 3.0 m < depth to water < 6.1 m | 108.78 | 0.67 | 0.14 | 0.23 |
| Depth to water > 6.1 m | | | | |
| With surface water | 422.17 | 0.74 | 0.08 | 0.29 |
| Without surface water (1980) | 77.70 | 0.00 | 0.75 | 0.26 |

compression will occur until the pore pressure dissipates as the water flows out of the soil. To account for the presence and effects of pore pressure, Terzaghi (1925) defined an effective stress. This is the stress 'felt' by the soil matrix and can be written as:

$$\sigma' = \sigma - u \quad (1)$$

in which σ' is the effective stress; σ is the total stress; and u is the pore water pressure.

The principle of effective stress provides the link between ground water withdrawal and subsidence. Within an aquifer, pore water pressure is equivalent to pressure head. As water is withdrawn from the aquifer and piezometric head drops, the effective stress on the aquifer increases even though the total stress remains constant. It is this increase in effective stress that causes the compression of the soil leading to subsidence.

The relationship between effective stress and the compression of clays is highly nonlinear. Fine-grained soils exhibit a 'memory' of past exposure to stress (Casagrande, 1932). The past maximum stress is recorded in the soil's structure and is called its preconsolidation stress, σ'_p . Compression is elastic (recoverable) at stresses less than the preconsolidation stress while compression beyond the preconsolidation stress is inelastic (unrecoverable). It is the inelastic compression, or consolidation, of fine-grained aquifer interbeds that causes the vast majority of subsidence problems in the San Joaquin Valley.

The IBS1 package calculates compaction based on changes in effective stress. The package assumes that

a change in piezometric head produces an equal but opposite change in effective stress in the aquifer, i.e. even as the piezometric head fluctuates, the total stress (i.e. geostatic load) remains constant. This assumption introduces error in shallow unconfined aquifers (Leake, 1991), but holds for deep or confined aquifers.

The package also assumes that the inelastic and elastic storage coefficients are constant. The values of these coefficients are actually functions of effective stress (Helm, 1976; Neuman et al., 1982; Rudolph and Frind, 1991), however, the assumption introduces little error if changes in effective stress are small in relation to the overall effective stress. Again, this assumption is problematic for shallow aquifers, but satisfactory for deeper ones (Leake, 1991). Neither of the above assumptions introduce significant error for the study area, because extensometer data have shown that almost all consolidation-induced subsidence in the valley occurs at depths between 105 and 610 m (Ireland et al., 1984).

The IBS1 package calculates the compaction of each model layer as:

$$\Delta b_e = S_{skc} b_0 \Delta h \quad (2)$$

$$\Delta b_i = S_{skv} b_0 \Delta h \quad (3)$$

in which Δb_e and Δb_i are the elastic and inelastic compaction, respectively; Δh is the change in head at the center of the layer; b_0 is the original thickness of the layer; and S_{skc} and S_{skv} are the elastic and inelastic storage coefficients, respectively. For all layers

included in the IBS1 package, the preconsolidation stress is actually recorded as a preconsolidation head, $h_p = \sigma'_p / \gamma_{water}$. For each time step, the total elastic and inelastic compaction is recorded and the amount of water released due to compaction is returned to the model water balance. Finally, if inelastic compaction has occurred, a new value of preconsolidation head is recorded.

The major weakness of the IBS1 package is its inability to directly consider the time delay of compaction. The IBS1 package assumes that compaction occurs instantaneously with change in head (Leake and Pradic, 1991). This approach is sufficient for aquifer systems with very thin compressible units and large model time steps, but thicker clay layers require a significant amount of time for pore pressures to dissipate.

There are two viable techniques for representing the time delay of consolidation. The first is to consider the delay in the analytical derivation of the land subsidence model as illustrated in the Interbed Drainage Package (IDP) by Shearer and Kitching (1994) and Shearer (1998). Similarly, Leake's (personal communication) IBS2 package allows for the delayed release of water from compressible, discontinuous clay beds within an aquifer.

The same result can be achieved numerically by dividing the larger low-conductivity units vertically into a number of smaller units. The residual pore pressure is then represented discretely across each compressible unit (Leake, 1990; Onta and Gupta, 1995). This second approach has been employed in this model and allows for the representation of time delay using the IBS1 package.

It should be emphasized that the IBS1 subsidence model only considers compaction due to increased effective stress caused by changing ground water levels. It does not consider subsidence due to hydrocompaction, withdrawal of gas and oil, deep-seated tectonic movement, or the dewatering of organic soils. Of these alternative causes of subsidence, only hydrocompaction has been significantly observed in the study area (Ireland et al., 1984). Hydrocompaction is subsidence that occurs as shallow, low-density soils are wetted for the first time. In the Los Banos-Kettleman City area hydrocompaction has resulted from the arrival of the California Aqueduct. Two sections of the California Aqueduct within the study region,

158–166 and 183–208 km, appear to be especially sensitive to hydrocompaction. Water was applied to these areas in the mid-1960s to exhaust the majority of hydrocompaction before the aqueduct was constructed. It has been assumed that all significant hydrocompaction occurred at that time and that it does not significantly contribute to subsidence during the modeling period (1972–2028).

5. Ground water flow model

Ground water levels for the Los Banos-Kettleman City area were previously modeled by Belitz et al. (1992) using MODFLOW (McDonald and Harbaugh, 1988). The focus of the research by Belitz et al. (1992) was drainage and water quality problems in the aquifer above the Corcoran clay layer. Although it does not simulate land subsidence, their model provides a calibrated estimate of ground water flow in the Los Banos-Kettleman City area. This paper adopts the Belitz et al. (1992) ground water model to simulate flow in the upper and lower aquifer, however, some modifications are made in order to: (1) consider ground water flow and subsidence in the aquifer system's low-conductivity layers; and (2) account for the time delay of consolidation. (For information on the selection of unaltered parameters for drainage, evapotranspiration, recharge, and boundary conditions, the reader should consult Phillips and Belitz (1991), Belitz et al. (1992) and Belitz and Phillips (1995)).

No modifications were made to the horizontal dimensions, model grid, and boundary conditions of the Phillips and Belitz (1991) model. The flow domain is discretized into 36 rows and 20 columns with a uniform nodal spacing of 1609 m in both the x - and y -directions (Fig. 3). The only significant change in geometry occurs in the representation of the vertical model layers. Fig. 4 shows the conceptual modifications made to the model. Most notably there is a change in how the low-conductivity layers (the Corcoran clay layer and clay interbeds) are represented. First, the larger clay layers have been divided into several smaller modeling layers. As discussed previously, this modification allows a head gradient to develop between each clay-modeling layer to mimic the presence of pore pressure and capture the

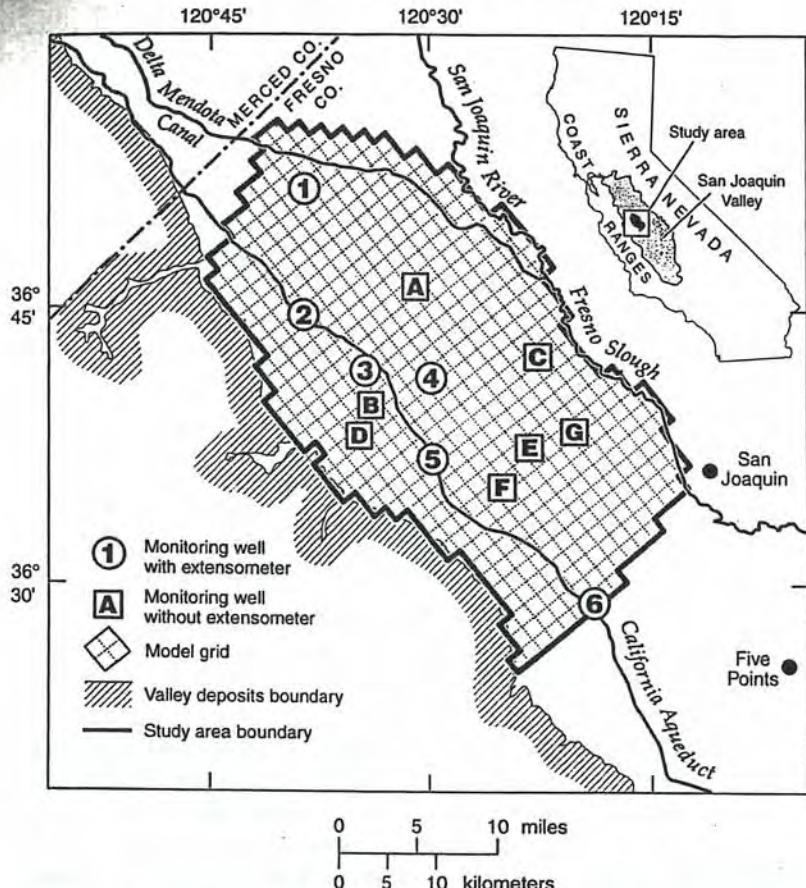


Fig. 3. Model grid and locations of monitoring wells and extensometers.

time delay of consolidation. The Corcoran layer was represented in this way. It was divided into three modeling layers comprising 55, 30, and 15% of the layer thickness (layers 6, 7, and 8, respectively, in Fig. 4). The thickness of the layers decreases with depth because the largest head changes occur in the confined aquifer. As head in the aquifer changes, the steepest head gradients in the Corcoran clay layer occur near the outer edge. The thinner layers are better able to capture this gradient.

Less hydrogeologic information is available for the interbed layers of the confined aquifer. Even if the location of each interbed was known, modeling the large number of interbeds separately would be computationally impractical. Instead of trying to map all the major interbeds in the confined aquifer, the interbeds are removed from the confined layer and

replaced by one large low-permeability layer at the bottom of the aquifer, as suggested by Ireland (1986). This bottom layer is assumed to have a uniform thickness of 95 m, located 305 m below the Corcoran. It is divided into five modeling layers with thicknesses of 3.05, 6.1, 12.2, 24.4, and 48.8 m (layers 10, 11, 12, 13 and 14, respectively, in Fig. 4). There is a no-flow boundary at the bottom of the layer, allowing drainage to occur only in the direction of the confined aquifer. The major limitation of this approach is that since the bottom layer is an artificial representation of the interbeds, hydrogeologic characteristics of the layer such as storage coefficients (elastic and inelastic) and vertical hydraulic conductivity cannot be verified by any field measurements. Thus, calibration will focus on choosing parameters for the layer such that their effect on land subsidence is

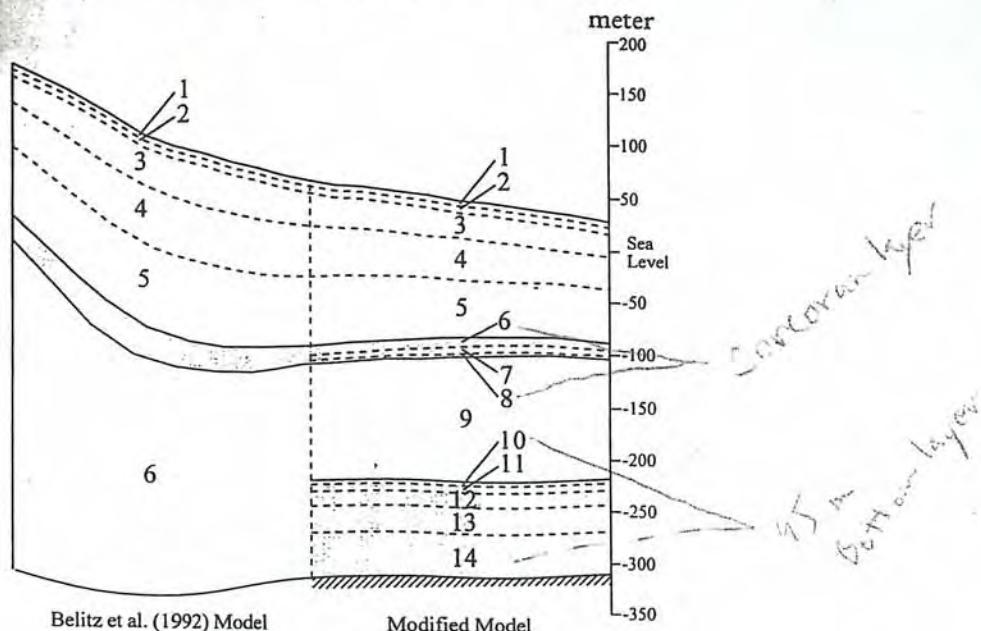


Fig. 4. Modifications to Belitz et al. (1992) model layers.

equivalent to the composite effect of the actual interbeds.

6. Initial and preconsolidation heads

Estimates for both initial and preconsolidation heads in the Corcoran and clay layers are the result of each layer's pressure history. Head levels reached a historical minimum just prior to the completion of the California Aqueduct. At that time, some amount of residual pore pressure likely remained in the thicker clay layers. Extensometer records show that inelastic subsidence continued following the completion of the aqueduct, even as heads in the aquifers began to recover. This evidence confirms that pore pressure was indeed dissipating from the clay layers at the beginning of the modeling period. Given this information, it is possible to generate a schematic drawing of head distribution for the time of maximum drawdown (Fig. 5). Heads in the aquifers are based on water table and potentiometric surface maps from 1972 (after Belitz et al., 1992). Heads in the low-conductivity layers are equal to the equilibrium piezometric head plus the residual pore pressure. The shape of the

residual pore pressure profile is assumed to be parabolic as predicted by Taylor (1948) for a time factor of 0.30. The selection of this time factor was somewhat arbitrary, but serves the purpose of generating a reasonable pore pressure profile. Given this shape, only the magnitude of the residual pore pressure need be determined to describe the entire profile. Unfortunately, the magnitude of residual pore pressure is a function of past changes in piezometric head and the thickness and hydraulic conductivity of the clay layers. Since this information is unknown, the magnitude of residual pore pressure is treated as a calibration parameter. Because of the relatively small changes in the water table, all residual pore pressure in the Corcoran layer is assumed to be the result of changes in piezometric head in the confined aquifer.

The above observations are only applicable for the time of maximum drawdown. The time of maximum drawdown is also a convenient time period to consider head levels because initial and preconsolidation heads are equal to each other. Thus, it is assumed that the initial heads for the model are equal to the head levels at the time of maximum historical drawdown. Although some amount of recovery occurred between the completion of

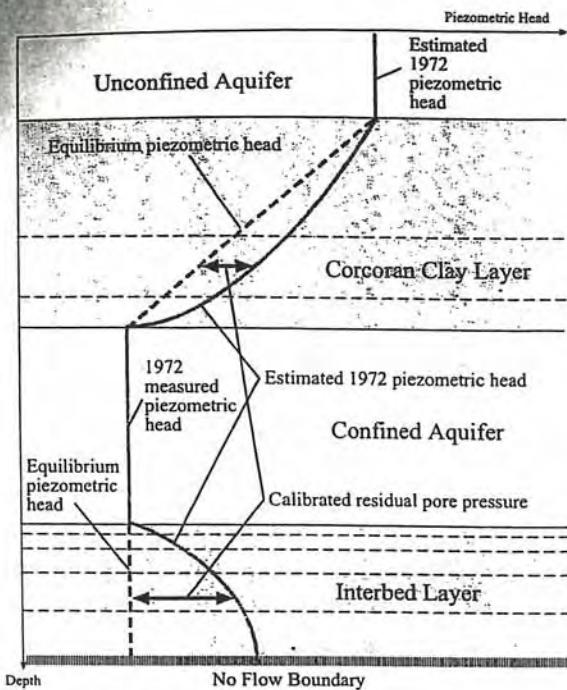


Fig. 5. Schematic drawing of initial and preconsolidation heads for the time of maximum drawdown.

the aqueduct and the beginning of the simulation model period (1972), the initial heads in the confined aquifer are sufficiently close to the historic minimum to produce acceptable results. Additionally, this assumption affects only the outermost portions of the Corcoran and clay interbed layers, resulting in minimal effect to overall land subsidence.

Initial heads in the aquifers remain largely unchanged from the Belitz et al. (1992) model. Modifications were made only where large jumps were observed in the initial time steps indicating that the head values were inconsistent with the rest of the model. This was particularly prevalent in the bottom layer of the unconfined aquifer (Belitz and Phillips, 1995). Although such inconsistencies usually stabilize in the first few time steps and have little effect on the long-term accuracy of the ground water flow portion of the model, they cause large fictional jumps in land subsidence. Thus, model head values for the bottom layer of the unconfined aquifer were set to simulated heads from a preliminary model run of four time steps (to 1974). This allowed sufficient time for any transient instability to dissipate.

7. Existing water supplies

There are two major sources of water in the Los Banos-Kettleman City region, surface water from the Central Valley Project (CVP) and ground water. The US Bureau of Reclamation's CVP is the largest water storage and delivery system in California, covering 29 of the State's 58 counties. It involves 18 federal reservoirs and 4 additional reservoirs jointly owned by California's State Water Project (California Department of Water Resources, 1998b; Chapter 3). Ground water pumping is one of the most difficult components to model because it has never been directly measured. The Belitz et al. (1992) model estimated pumping magnitudes using the same nine subareas designated by Gronberg and Belitz (1992), adopting their 1980 water budget values for all model years. This budget allows pumping rates to vary between subareas, but distributes pumping uniformly within each subarea. The spatial distribution of pumping in the Belitz et al. (1992) model is adopted in this paper, but the yearly magnitude estimates are altered. The assumption of constant pumping in all years was satisfactory for the purposes of their report (Belitz et al., 1992; Belitz and Phillips, 1995), but does not capture the pore pressure fluctuation necessary to model land subsidence.

To estimate yearly fluctuation in ground water pumping, this paper uses records of CVP water delivery from the Westlands and Panoche Water Districts. Fig. 6 illustrates the relationship assumed between CVP water delivery and ground water pumping rates. Several assumptions have been made in creating this figure. It is assumed that the Gronberg and Belitz (1992) water budget is appropriate for years in which 100% of the CVP contract water is available. During years of reduced surface water availability, the shortage can be met by reducing demand (land retirement), increasing irrigation efficiency, purchasing outside water through temporary water transfers, or increasing ground water pumping. Increasing efficiency and water transfers are inexpensive alternatives for years with small reductions in CVP water. For increasing levels of drought, however, these options become very costly or unavailable. Thus, an increasing amount of the shortage must be met with ground water.

The assumed line of combined ground water and

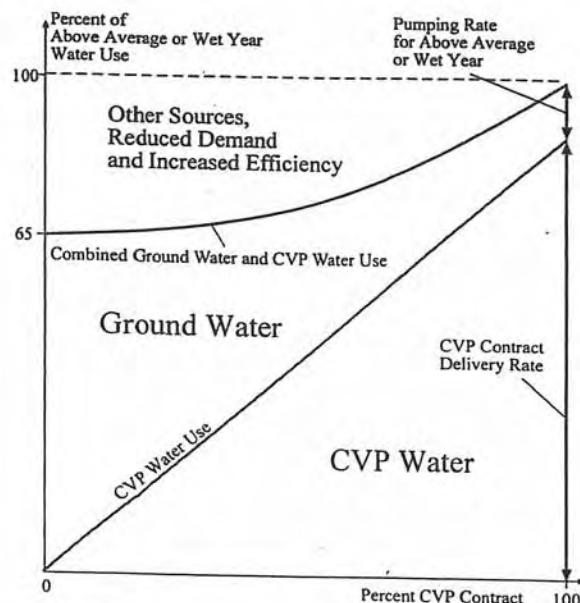


Fig. 6. Relationship between CVP water delivery and ground water pumping rates.

CVP water use can be mathematically described as:

$$\Phi_c = 0.0022\Phi_s^2 + 0.13\Phi_s + 65 \quad (4)$$

in which Φ_c is the percent of normal, combined ground water and surface water use; and Φ_s is the percent of contracted surface water. The parameters for this equation were developed through trial and error during the model calibration. Unfortunately, because no ground water pumping measurements exist, there is no way to verify the accuracy of Eq. (4) except by examining the accuracy of the simulated ground water levels. The relationship in Eq. (4) not only assures consistent estimation of yearly pumping rates for the calibration period, but also provides an estimate for future pumping rates based on the availability of surface water.

8. Model limitations

As in the Belitz et al. (1992) model, the model formulated in this study uses yearly stress periods because most of the data (water table levels, subsidence rates, CVP deliveries, etc.) are only available at yearly intervals. The major weakness of this approach is its effect on pumping. By averaging the pumping out over the entire year, the higher drawdowns occurring during the

summer months are lost. This is significant for the land subsidence portion of the model because most of the subsidence actually occurs during these periods of high drawdown. This can be compensated for by altering some of the other model parameters, but it should be noted that the piezometric heads predicted by the model are artificially high during the summer months.

In addition to the temporal averaging of pumping rates, pumping is also averaged spatially over each grid cell. During calibration, measured ground water levels were assigned to the center of the grid cells and compared with the spatially and temporally averaged model-computed ground water levels. Although some information is lost in the spatial and temporal averaging of parameters, it is unavoidable in numerical modeling. Pumping rates are also averaged across water budget sub-areas in the simulation model. Since pumping is not applied to individual wells, some localized subsidence cannot be captured by the model.

9. Calibration

9.1. Piezometric head

Calibration of the model encompasses matching

simulated piezometric head levels and land subsidence with corresponding observed values across the study area. Fig. 7 shows the model results following calibration plotted against the observed piezometric head for four California Department of Water Resources (DWR) monitoring locations (Fig. 3, Table 2). By using the aquifer parameters found by Belitz et al. (1992), it was possible to produce relatively accurate results for piezometric head with modification to the pumping rates only. Proper drawdown during years of drought was achieved using the scheme described in Section 7. In addition to determining the best equation to define combined ground water and surface water use (see Eq. (4)), the calibration dictated one other significant change.

The water budget for the Belitz et al. (1992) model includes a portion of the Westlands Water District that relies strictly on ground water. Following construction

of the water budget, however, improvements were made in the delivery system to bring CVP water to portions of this area. This was evident during the calibration trials when predicted head levels were significantly below those observed in these portions of the Westlands Water District. To address this problem, the original water budget is retained for the model years up to 1980, but it is assumed that CVP water replaces 25% of the pumping in 1981 and replaces 50% in 1986.

9.2. Land subsidence

Land subsidence in the San Joaquin Valley has been documented using both extensometers located at wells throughout the Valley and level runs along the California Aqueduct. The six extensometers included in this study were installed by the US

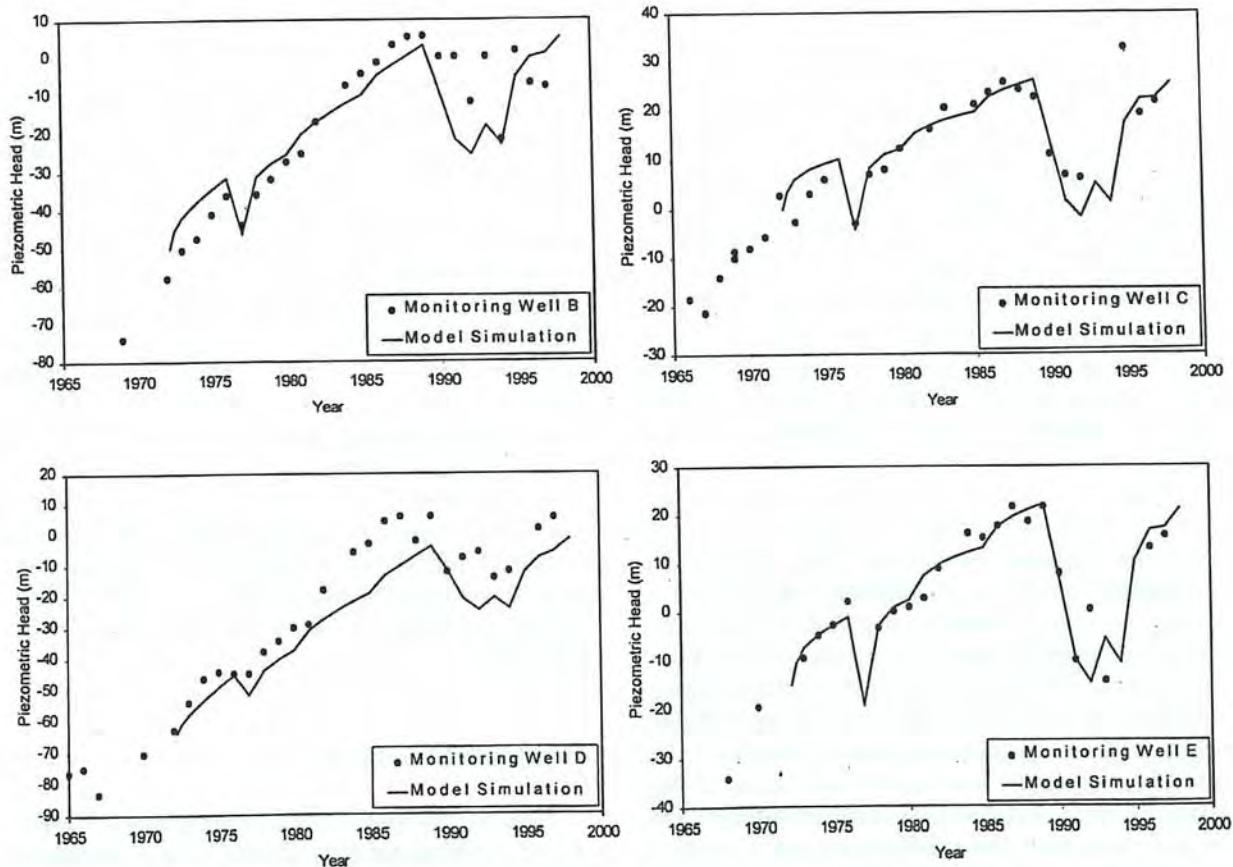


Fig. 7. Observed and simulated piezometric heads at four monitoring well locations.

Table 2

Well numbers for extensometers and monitoring wells (*: information considered confidential by the California DWR. Contact owner of individual well for more information.)

| Observation location | Well number | Year of installation | Screen interval (m) | Monitored interval by extensometer (m) |
|---|-------------|----------------------|---------------------|--|
| <i>Extensometers and monitoring wells</i> | | | | |
| 1 | 12/12-16H2 | 1958 | 235–277 | 0–305 |
| 2 | 13/12-20D1 | 1961 | 130–203 | 0–208 |
| 3 | 14/12-12H1 | 1965 | 226–285 | 0–297 |
| 4 | 14/13-11D6 | 1961 | 345–365 | 0–414 |
| 5 | 15/13-11D2 | 1965 | 274–293 | 0–292 |
| 6 | 16/15-34N1 | 1958 | 321–339 | 0–610 |
| <i>Monitoring wells only</i> | | | | |
| A | 13/13-10R1 | * | * | — |
| B | 14/12-25D1 | * | * | — |
| C | 14/14-02N2 | * | * | — |
| D | 15/12-01R1 | * | * | — |
| E | 15/14-02B1 | * | * | — |
| F | 15/14-21E1 | * | * | — |
| G | 14/15-32N3 | * | * | — |

Geological Survey (USGS) and are now monitored by the San Joaquin District of the California DWR. Three of the extensometers were abandoned in the 1970s and thus provide only a partial record for the calibration period. For those extensometers that continue through the entire time interval (1972–1998), a small portion of the data is missing from the record (1979–1984). Fortunately, the missing portion corresponds to a time of relatively uniform rebound, assumed at a rate equal to the average of the rebound in the years 1978 and 1985. Calibrated model results versus observed subsidence are shown for four extensometer locations (Table 2) in Fig. 8.

Extensive level runs were conducted for the Los Banos-Kettleman City region throughout the 1950s and 1960s. Although more recent data could not be accessed for this project, the previous level runs give a good indication of subsidence trends for the area. Fig. 9a is a contour map of the measured subsidence from 1926 to 1972, while Fig. 9b shows the predicted subsidence from 1972 to 1998. Although the different time periods do not allow for direct comparison, the subsidence trends for each period are similar. There appears to be a small shift in the peak of subsidence to the east. Additional data would be required to verify if this represents a real shift in subsidence or is related to the choice of calibration parameters.

There are four major subsidence parameters determined during the calibration process: hydraulic conductivity, elastic storage coefficient, inelastic storage coefficient, and preconsolidation head. For the Corcoran clay layer, the storage and conductivity parameters are taken as the average of measured values from Ireland et al. (1984) and only the preconsolidation heads are modified during calibration. Because of the fictional nature of the interbed layer, however, there is no correlation between its storage parameters and values measured in the field. All four major parameters for this layer can only be determined through calibration. The final choices for these parameters were achieved through trial and error. Although the computational effort required to run the model makes a statistically rigorous calibration numerically impractical, a sensitivity analysis was performed to aid in the selection of model parameters.

10. Sensitivity analysis

A sensitivity analysis was performed with respect to vertical hydraulic conductivity, elastic and inelastic storage coefficients, and preconsolidation head. Although the sensitivity analysis revealed similar

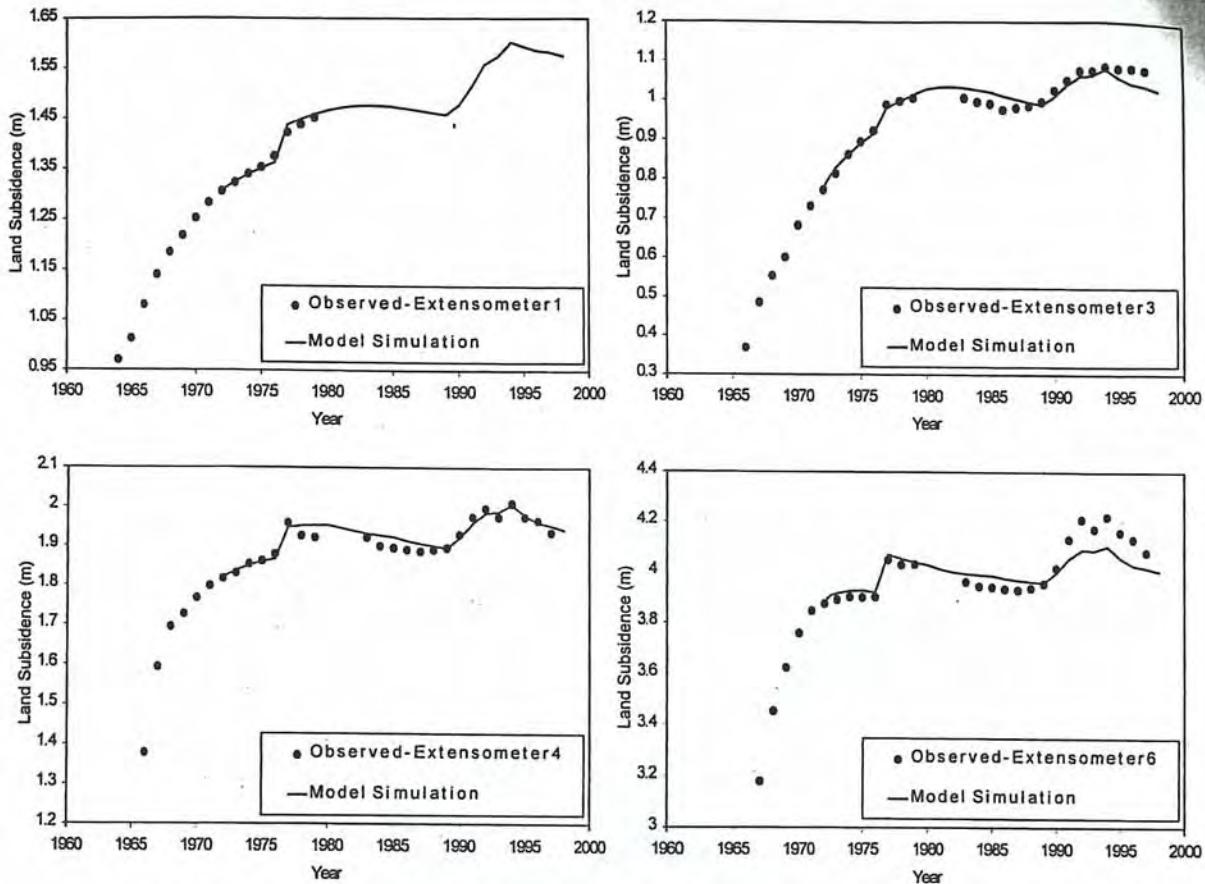


Fig. 8. Observed and simulated land subsidence at four extensometer locations.

results at all observation sites, typical results are shown for only one location (Extensometer 3).

10.1. Hydraulic conductivity

Hydraulic conductivity is represented both in vertical and horizontal directions. The horizontal conductivity in the interbed layers is of little interest, however, due to small head gradients along long flow paths in the horizontal direction. The average horizontal hydraulic conductivity values for the interbed layers documented by Ireland et al. (1984) are used in the model. Conversely, the vertical conductivity greatly affects the performance of the model. It determines the rate pore pressure leaves the fine-grained layers and hence, the rate of subsidence. Fig. 10a shows the model results obtained

using fourfold and one-fourth of the calibrated vertical hydraulic conductivity values for the interbed layers (0.0762 m/yr). As can be seen from Fig. 10a, the rate and magnitude of consolidation is highly dependent upon the vertical hydraulic conductivity while the general trend of the subsidence is not greatly affected.

10.2. Elastic and inelastic storage coefficients

The elastic and inelastic storage coefficients determine the magnitude of subsidence for a given change in hydraulic head. The elastic storage coefficient can be examined independently of the inelastic storage coefficient during periods of rebound. The small volume of water flowing from the low-conductivity layers during elastic compaction means there is

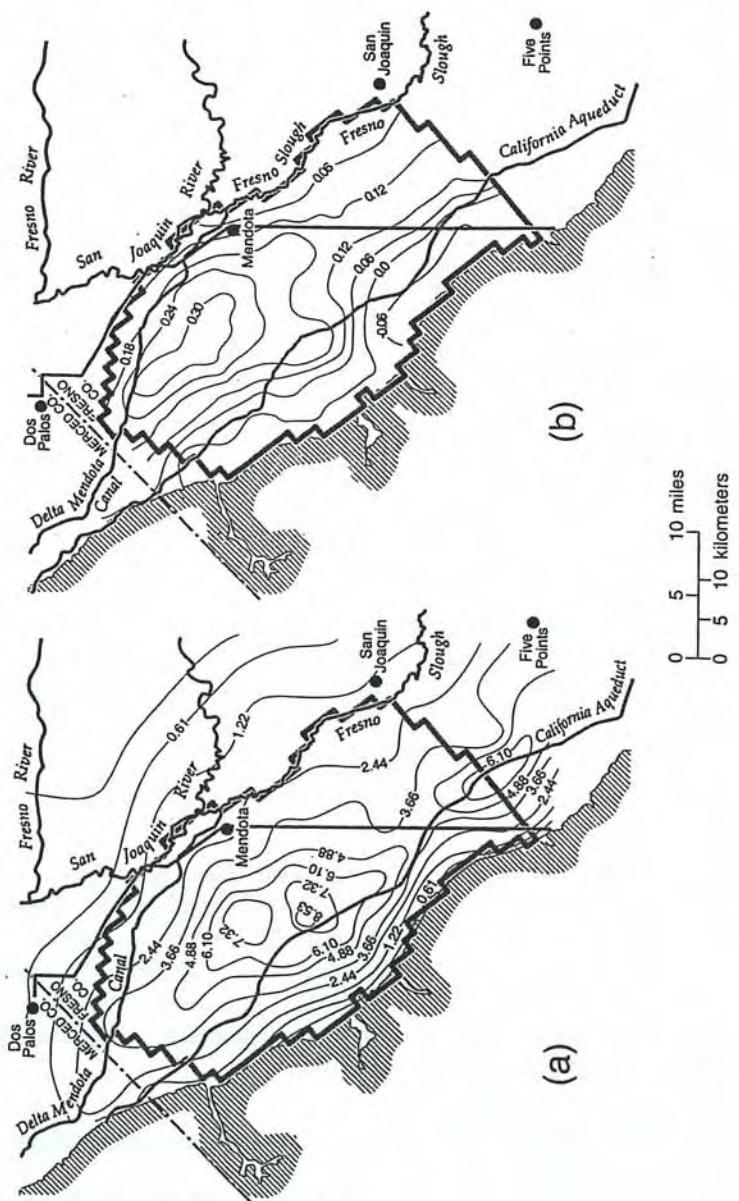


Fig. 9. (a) Observed land subsidence for the Los Banos-Kettleman City area, 1926–1772 (Ireland et al., 1984); and (b) simulated land subsidence for the Los Banos-Kettleman City area, 1972–1998.

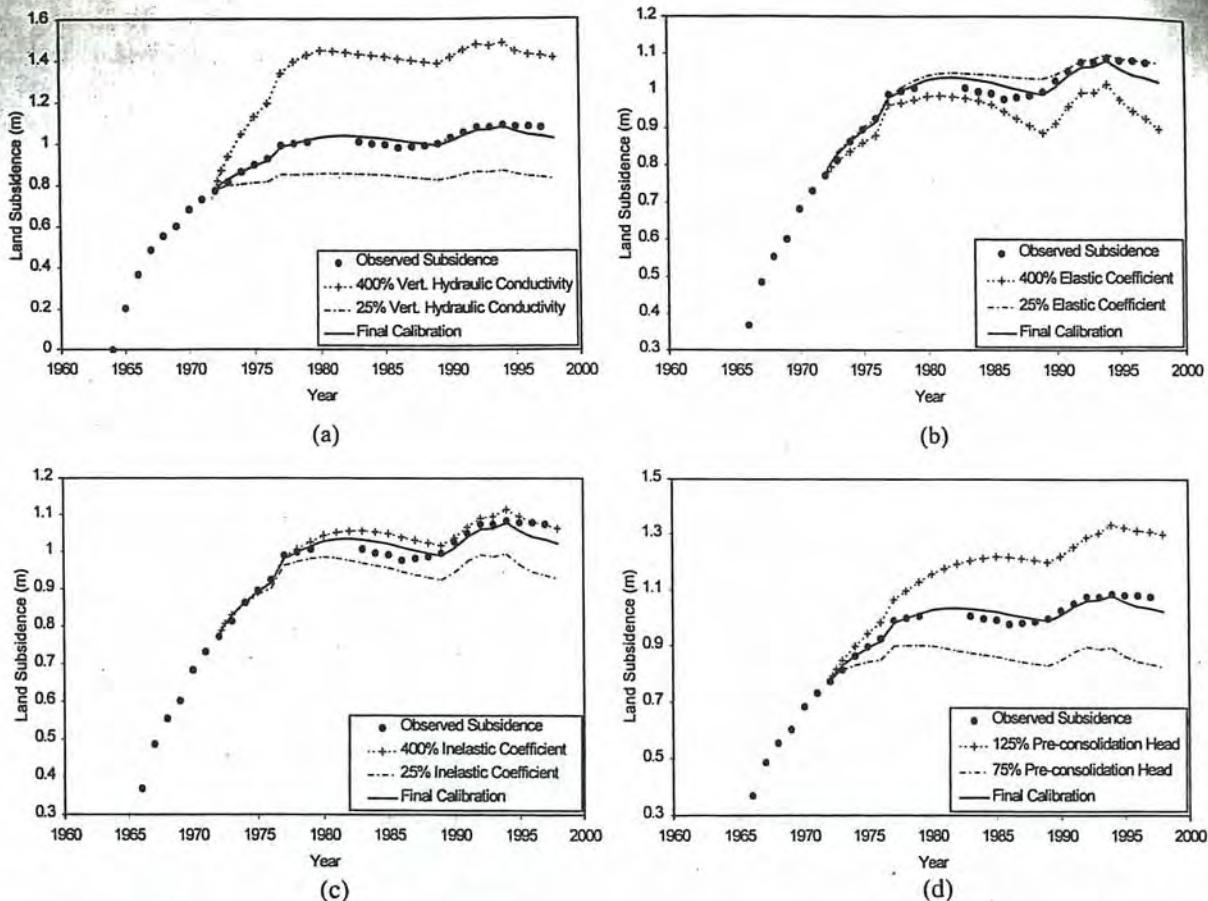


Fig. 10. Sensitivity of subsidence at Extensometer 3 with respect to: (a) Vertical hydraulic conductivity; (b) elastic storage coefficient; (c) inelastic storage coefficient; and (d) preconsolidation heads.

much less time delay associated with rebound than with consolidation. Hence, the rate of subsidence during rebound is almost exclusively governed by the elastic storage coefficient. This makes the elastic coefficient the easiest parameter to calibrate because it can be chosen, virtually independent of the other parameters, to match the observed rebound rate.

The contribution of the inelastic coefficient is much more difficult to isolate. During inelastic compaction a significant volume of water is expelled from the compressible model layers. Because the rate of this expulsion is governed by the vertical hydraulic conductivity, the rate of inelastic consolidation is dominated by the vertical conductivity, not the inelastic storage coefficient. The latter determines how quickly the preconsolidation head drops in each

layer as consolidation occurs. Thus, it is an important parameter in determining when inelastic compression starts and stops. Fig. 10b and c show the model results obtained using fourfold and one-fourth of the calibrated elastic ($1.35 \times 10^{-5} \text{ m}^{-1}$ for the Corcoran layers and $2.71 \times 10^{-5} \text{ m}^{-1}$ for the confined layers) and inelastic ($1.35 \times 10^{-3} \text{ m}^{-1}$ for the Corcoran layers and $2.12 \times 10^{-3} \text{ m}^{-1}$ for the confined layers) storage coefficients, respectively.

10.3. Preconsolidation heads

The preconsolidation heads for the Corcoran and interbed layers are determined using the process described earlier. If a parabolic profile is assumed as shown in Fig. 5, only the upper bound of residual pore

pressure need be determined through calibration. This upper bound of residual pore pressure was first approximated using head values observed in the confined aquifer in 1943, when intense ground water withdrawal began to cause the most serious subsidence. The 1943 heads essentially represent predevelopment conditions and the maximum possible preconsolidation heads. These values were then lowered during the calibration process to match observed subsidence.

Preconsolidation head has two effects on the model. First, an increase in preconsolidation head results in an increased rate and magnitude of subsidence because of the larger head gradient between the aquifers and the compressible layers. Second, an increase in preconsolidation head results in longer periods of subsidence since head levels must rise higher for rebound to begin. This second effect makes it possible to differentiate between the effects of an increase in preconsolidation head and an increase in vertical conductivity. Fig. 10d shows the model results obtained using 125 and 75% of the calibrated residual pore pressure values.

11. Predicting future subsidence potential

11.1. Development of future drought scenarios

Because ground water pumping rates are dependent on surface water availability, reliable long-term flow forecasting is required for subsidence prediction in the Los-Banos Kettleman City area. Unfortunately, the main source of surface water for the region, the CVP, has been in place for only 30 years, which is not long enough to generate a statistically reliable delivery forecast. However, since the majority of the Los Banos-Kettleman City CVP water comes from the Sacramento Valley, the Sacramento Four River Index (SFRI) can be used to estimate future surface water supplies in the Los Banos-Kettleman City area.

The SFRI (also known as the Sacramento 40–30–30 Index) is computed as a weighted average of the current year's April–July unimpaired runoff forecast (40%), the current water year's October–March unimpaired runoff forecast (30%), and the previous year's index (30%). A cap of $12.33 \times 10^9 \text{ m}^3$ is speci-

fied on the previous year's index to account for required flood control reservoir releases during wet years. Unimpaired runoff (calculated as the sum of Sacramento River flow near Red Bluff, Feather River inflow to Oroville, Yuba River at Smartville, and American River inflow to Folsom) is the river production unaltered by water diversions, storage, exports, or imports. A water year with a SFRI equal to or greater than $11.34 \times 10^9 \text{ m}^3$ is classified as 'wet'. A water year with an index equal to or less than $6.66 \times 10^9 \text{ m}^3$ is classified as 'critical' (California Department of Water Resources, 1998a; Chapter 3).

The best fit relationship between the SFRI and the CVP delivery rates for years classified by the California DWR as 'below average,' 'dry,' or 'critical,' can be mathematically described ($R^2 = 0.7264$) as:

$$\Phi_s = 3.23 \times 10^{-7} (\text{SFRI})^{2.2839} \quad (5)$$

in which Φ_s is the percent of contracted CVP surface water and SFRI is in 10^9 m^3 .

Historical records of the SFRI are available from 1906 to the present, which is enough data to generate future scenarios using the bootstrap method. The bootstrap method is based on the assumption that a sample set adequately represents the entire population and that new scenarios can be generated by sampling with replacement from the original set. The major restriction of this method is that all sample points must be independent. Although the SFRI has a one-year lag dependency, the auto-correlation function of the yearly unimpaired runoff reveals no temporal correlation. Thus, the bootstrap method may be used to generate unimpaired runoff scenarios by randomly sampling with replacement from the historical unimpaired runoff record. These scenarios can in turn be transformed to SFRI scenarios using Eq. (5).

The severity of drought in a water availability forecast can be measured in several ways. Two such ways suggested by Shen and Tabios (1996) are average drought severity and cumulative deficit. Distribution functions for each criterion were created using the drought measurements of five hundred 30-year water availability scenarios randomly generated using the bootstrap method. Because both criteria have advantages, a single realization with a 5% probability of exceedance for both drought categories is

Table 3
Future water delivery scenario

| Year | SFRI (10^9 m^3) | CVP delivery rate (%) | CVP delivery rate alternative C (%) |
|--|--------------------------------|--------------------------|--|
| 1999 | 7162 | 79 | 64.7 |
| 2000 | 5335 | 40.3 | 33.4 |
| 2001 | 5673 | 46.4 | 38.3 |
| 2002 | 11,549 | 100 | 100 |
| 2003 | 11,130 | 100 | 100 |
| 2004 | 8738 | 100 | 100 |
| 2005 | 12,059 | 100 | 100 |
| 2006 | 6635 | 66.3 | 54.5 |
| 2007 | 7381 | 84.6 | 69.3 |
| 2008 | 5231 | 38.5 | 31.9 |
| 2009 | 4882 | 32.9 | 27.3 |
| 2010 | 12,494 | 100 | 100 |
| 2011 | 12,049 | 100 | 100 |
| 2012 | 10,714 | 100 | 100 |
| 2013 | 6729 | 68.5 | 56.3 |
| 2014 | 12,223 | 100 | 100 |
| 2015 | 5831 | 49.5 | 40.8 |
| 2016 | 9832 | 100 | 100 |
| 2017 | 8295 | 100 | 90.1 |
| 2018 | 14,549 | 100 | 100 |
| 2019 | 5864 | 50.0 | 41.3 |
| 2020 | 6637 | 66.4 | 54.6 |
| 2021 | 4154 | 22.8 | 19.0 |
| 2022 | 11,101 | 100 | 100 |
| 2023 | 16,358 | 100 | 100 |
| 2024 | 8331 | 100 | 91.0 |
| 2025 | 12,652 | 100 | 100 |
| 2026 | 8834 | 100 | 100 |
| 2027 | 8050 | 100 | 84.2 |
| 2028 | 9393 | 100 | 100 |
| Average shortfall (Percentile) = 1982.7 (95.6%) | | | |
| Cumulative drought (Percentile) = 23,793 (95.2%) | | | |

considered. Table 3 summarizes the SFRI and corresponding CVP delivery rates for the selected realization.

11.2. Potential management alternatives

Alternative A is the current best-fit relationship between surface water delivery rates and SFRI. In essence, this alternative represents maintaining current management practices. For reasons given previously, it is probably unreasonable to expect current surface water supplies to remain undiminished. Additionally, drainage problems documented by Belitz and Phillips (1995) indicate some change in water management is needed for agriculture to remain viable in the Los Banos-Kettleman City region. Two additional alternatives addressing these issues are also considered.

As one possible solution to the drainage problems in the region, Belitz and Phillips (1995) proposed a combination of increased ground water pumpage and reduced recharge. Their proposal is considered as Alternative B and is summarized by the water budget given in Table 4. It is an attractive alternative because it would reduce many of the drainage problems in the region. It would also require only minimal investment, as all increases in pumping would occur at existing wells. It is assumed that the relationship between CVP delivery rates and SFRI remains the same as in Alternative A (Eq. (5)), but that the contract delivery rate is reduced to the levels proposed by Belitz and Phillips (1995).

Alternative C reduces surface water demand not by changing the total contracted amount of surface water,

Table 4
Alternative B proposed water budget (from Belitz and Phillips, 1995)

| Subarea | Area (km^2) | Surface water delivery (m/yr) | Ground water pumpage (m/yr) | Ground water recharge (m/yr) |
|--------------------------------|------------------------|----------------------------------|--------------------------------|---------------------------------|
| Firebaugh | 189.07 | 0.56 | 0.15 | 0.14 |
| Panoche | 124.32 | 0.48 | 0.15 | 0.17 |
| Broadview | 41.44 | 0.61 | 0.15 | 0.16 |
| Tranquility | 77.70 | 0.57 | 0.24 | 0.22 |
| San Luis | 77.70 | 0.38 | 0.27 | 0.20 |
| Westlands | | 0.00 | 0.00 | 0.00 |
| Depth to water < 3.0 m | 251.23 | 0.41 | 0.27 | 0.12 |
| 3.0 m < depth to water < 6.1 m | 108.78 | 0.48 | 0.29 | 0.19 |
| Depth to water > 6.1 m | | 0.00 | 0.00 | 0.00 |
| With surface water | 422.17 | 0.55 | 0.23 | 0.24 |
| Without surface water (1980) | 77.70 | 0.37 | 0.37 | 0.26 |

but by changing the relationship between percent delivery rate and SFRI. During wet years there is no reduction in total surface water use. During drier years, however, surface water use is reduced up to 20% for years of moderate drought, with more modest reductions during years of severe drought (Table 3). Although this alternative would provide a reduction of up to $0.19 \times 10^9 \text{ m}^3$ of surface water during years of drought, it does little to address the drainage and water quality problems facing the region.

12. Optimization model

A linear optimization model was formulated to find the maximum increase in ground water withdrawal without causing any inelastic compaction during the 30-year planning horizon. In order to eliminate the nonlinearity associated with subsidence, heads are allowed to fluctuate only within the region of elastic compaction. This is accomplished by setting the preconsolidation head as the lower bound for ground water levels in the confined aquifer. For simplicity in computation, the optimization model assumes uniform pumping over each pumping subarea and heads are only monitored at one characteristic location in each subarea. The response function approach (Gorelick, 1983; Yeh, 1992) is used to couple the simulation and optimization models. In this approach, the model is first allowed to reach a steady state under normal-year pumping conditions. Each pumping subarea is then separately subjected to a unit impulse of additional pumpage in the first period with no disturbance thereafter, and the system's response to each stress is monitored over the entire planning period.

The objective function of the optimization model maximizes the total ground water withdrawal at all

production wells during the forecast period:

$$\text{Max } Z = \sum_{n=1}^{\text{NTS}} \sum_{k=1}^{\text{NOW}} Q(k, n) \quad (6)$$

in which Z is the value of the objective function (L^3/T); $Q(k, n)$ is volume of water withdrawn from the k th well field during the n th time period (L^3/T); NTS is the total number of periods; and NOW is the total number of well fields.

The constraint set of the model includes the following conditions and specifications:

1. The ground water demand above the normal year demand, GWD(n), needs to be met:

$$Q(k, n) \geq \text{GWD}(k, n) \quad \forall k, \forall n \quad (7)$$

2. Ground water withdrawals are related to drawdowns through the response equations:

$$s(l, n) = \sum_{i=1}^{\text{NTS}} \sum_{k=1}^{\text{NOW}} \beta(l, k, n - i + 1) \cdot Q(k, n) \quad \forall l, \forall n \quad (8)$$

in which $s(l, n)$ is the drawdown at the l th observation point; $\beta(\cdot)$ are the response coefficients; and i is the pumping period index.

3. Drawdowns are not allowed to exceed the difference between the initial water level and the preconsolidation head level and maximum pumpage rates at the production wells must not be exceeded:

$$s(l, n) \leq s_{\text{MAX}}(l, n) \quad \forall l, \forall n \quad (9)$$

$$Q(k, n) \leq Q_{\text{MAX}}(k) \quad \forall n \quad (10)$$

Maximum pumpage rates for all subareas are set at 0.4 m/yr to reflect the capacity of existing well fields.

Table 5
Maximum drawdowns and areas for pumping subareas

| | Water budget subareas | | | | | | | | |
|--------------------------|-----------------------|--------|--------|--------|--------|--------|--------|--------|--------|
| | 1 | 6 | 8 | 9 | 10 | 11a | 11b | 11c | 11d |
| $S_{\text{max-dry}}$ (m) | 43.16 | 38.039 | 46.573 | 52.578 | 68.641 | 46.665 | 51.328 | 59.527 | 82.205 |
| $S_{\text{max-wet}}$ (m) | 29.23 | 25.42 | 29.718 | 33.406 | 53.584 | 30.114 | 32.126 | 35.631 | 65.288 |
| Area (km^2) | 189.07 | 77.7 | 124.32 | 41.44 | 77.7 | 251.23 | 108.78 | 422.17 | 77.7 |

The total area and maximum allowable drawdown for each water budget subarea are given in Table 5. Two different sets of maximum allowable drawdown are used in the optimization model for wet and dry periods. The maximum allowable drawdown in wet years corresponds to the preconsolidation head in the bottom sub-layer of the clay interbed unit (i.e. the maximum preconsolidation head for any compressible layer). Because of the low conductivity of the clay layer, however, piezometric head levels in the confined aquifer may drop below this value for short periods without causing inelastic subsidence. To take advantage of this additional capacity, the maximum allowable drawdown during dry periods corresponds to the preconsolidation head in the outermost layer of the clay interbed unit. This adjustment provides for additional drawdown during periods of drought, but

sustains long-term head levels above all values of preconsolidation head.

The response coefficients in Eq. (8) were generated using MODFLOW (McDonald and Harbaugh, 1988) following model calibration. The linear optimization model formulated above was solved using GAMS (Brooke et al., 1992). The pumping rates calculated by the optimization model were then returned to the simulation model to estimate land subsidence.

13. Results

Fig. 11 presents the predicted total subsidence for the years 1999–2028 at the four aforementioned extensometer locations. Contour maps of land subsidence across the entire study area are shown in Fig. 12.

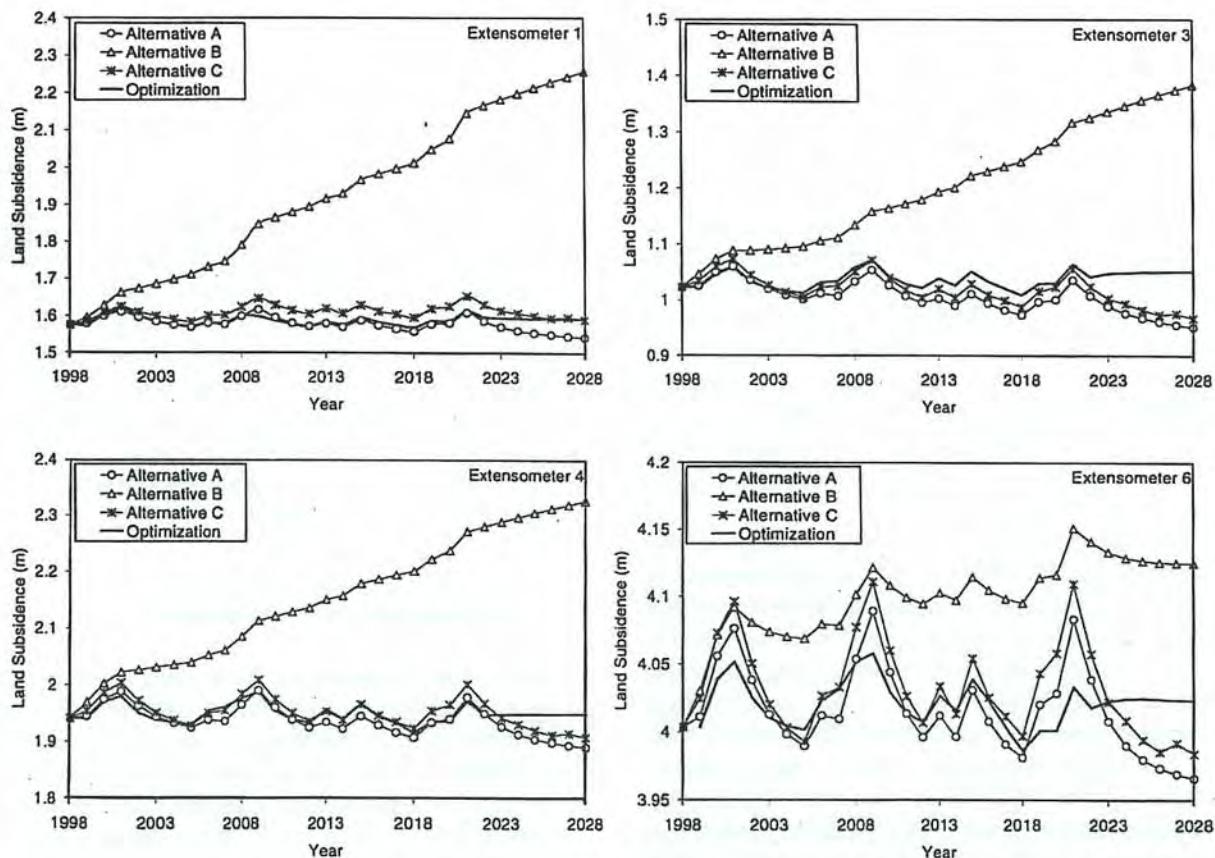


Fig. 11. Model prediction of total subsidence for 1999–2028 at four extensometer locations.

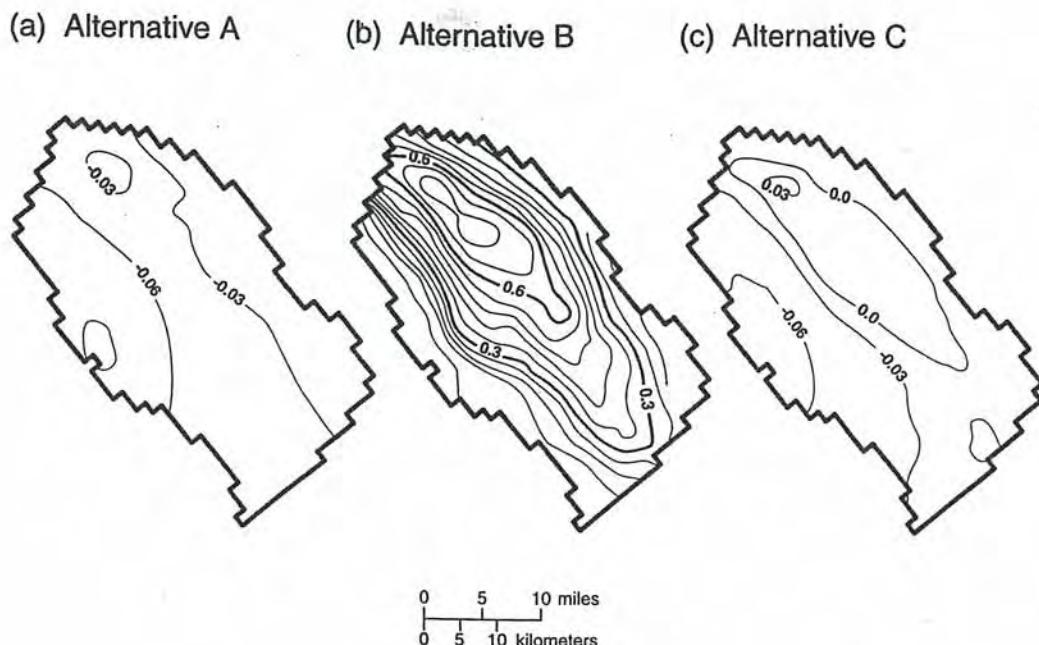


Fig. 12. Contour maps of simulated subsidence (1999–2028).

These figures indicate that although there is some elastic compaction during years of drought in Alternative A, the overall trend is toward rebound. In contrast, Alternative B causes significant subsidence, especially in the northwest corner of the study area. As in Alternative A, Alternative C produces a small amount of elastic compaction, with minimal long-term subsidence. The optimization results produce subsidence similar to that of Alternatives A and C. The only major difference is a period of little change during the final seven years while Alternatives A and C show significant rebound.

The total maximum groundwater withdrawal for the entire system (from a total of 529 production wells) over the 30-year planning horizon, without leading to inelastic subsidence, is estimated $8.27 \times 10^9 \text{ m}^3$, using the optimization model. The maximum ground water withdrawal for each water budget subarea is shown in Fig. 13, after standardizing it by the number of production wells in each subarea. Ground water withdrawal can be significantly increased without causing any inelastic compaction in subareas 1 (Firebaugh) and 6 (Tranquility) which are located along the river on the eastern side of the

basin. In contrast, only very modest pumping increases above the minimum required can occur in subareas 10 and 11c along the no-flow boundary to the west without leading to inelastic subsidence. Ground water supplies are intensely operated in almost all of the subareas during the last years of the future scenario. This is the result of one of the major assumptions of the optimization model. Because the optimization model has perfect foresight, following the final drought period it no longer needs to plan for future drought and can increase pumping until ground water levels reach the point of maximum drawdown.

14. Conclusion and recommendations

The model presented in this study provides a method for evaluating the future implications and consequences of proposed water use alternatives in land subsidence prone areas. Although the simulation model cannot represent the complex ground water system in its entirety, it successfully matches historical head and subsidence data across the Los Banos-Kettleman City area.

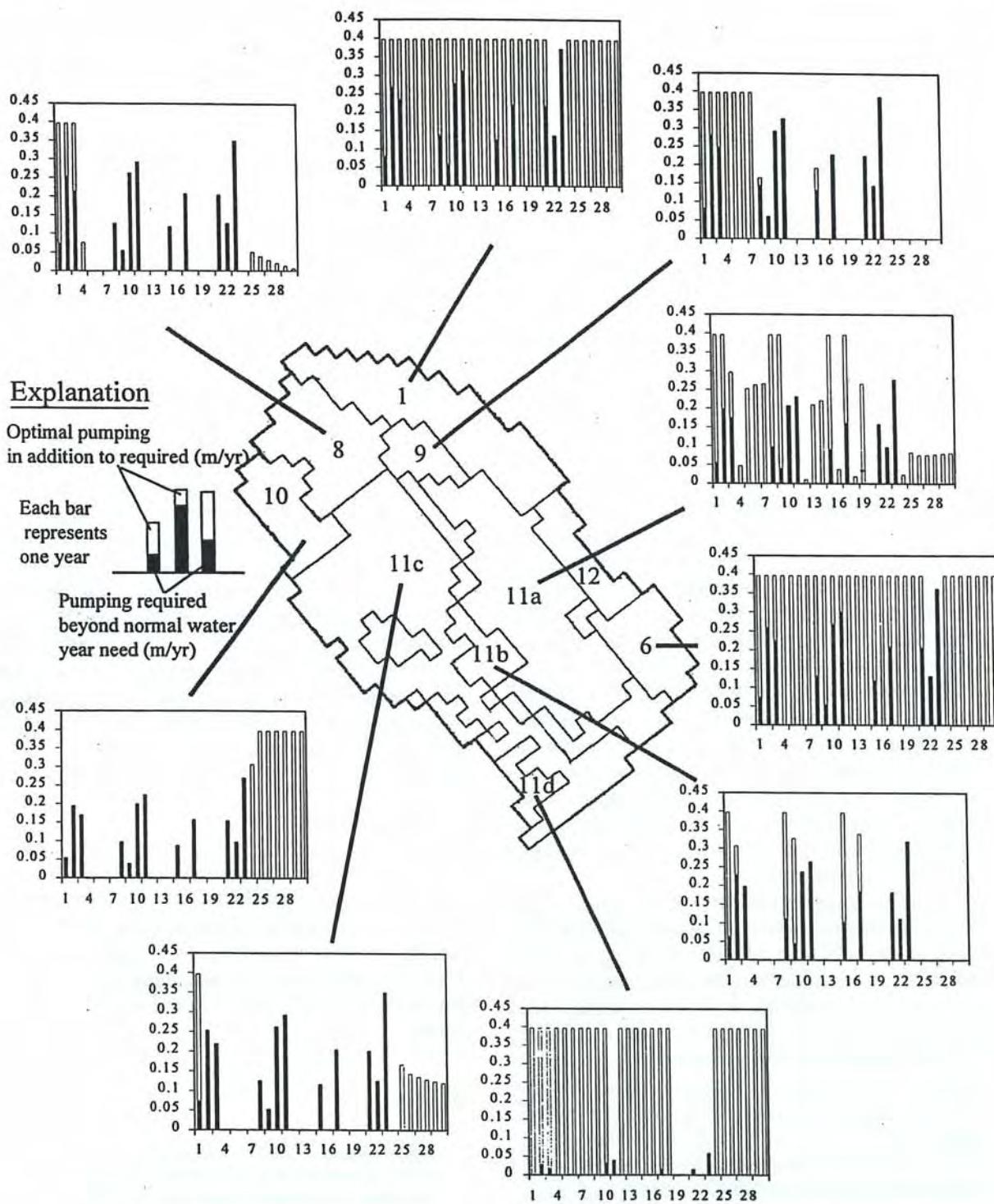


Fig. 13. Maximum potential ground water withdrawal from each sub-area without causing unrecoverable compaction.

Model results indicate that if current practices can be sustained, land subsidence will not be a serious problem in the next thirty years. Although head levels are significantly reduced and some elastic compaction does occur during periods of drought, there is enough storage in the underlying aquifers to prevent most unrecoverable subsidence. However, with the continued growth of urban populations to the south and the passage of the CVPIA and its implications on water exportation from the north, there seems to be little hope of sustaining current practices.

The alternative water budget proposed by Belitz and Phillips (1995) achieves a reduction in surface water dependency by increasing irrigation efficiency and ground water pumping. This proposal is also meritorious for its positive effect on drainage problems in the region. Unfortunately, this alternative produces significant inelastic subsidence during the future scenario considered in this paper.

There are two possible reasons the Belitz and Phillips (1995) did not recognize the proposed water budget's potential for subsidence. First, in their analysis, subsidence was assumed to occur only when the piezometric head in the confined aquifer falls below its historic minimum. This neglects the presence of residual pore pressure, which causes inelastic compaction to begin at heads much greater than the historic aquifer minimum. Second, in the water budget used by Belitz and Phillips (1995), the surface water delivery rate was assumed to be constant for the next 45 years. Much of the predicted subsidence would be eliminated using the same assumption for our model. The proposed water budget lowers head values just enough, however, that when drought years are included, there is not enough storage to prevent subsidence from occurring.

The final alternative examined was a shift in the relationship between available surface water (SFRI) and the amount of CVP water used in the region. Like Alternative A, this alternative limits subsidence to an acceptable rate. Although it does not reduce the surface water required during wet years, it reduces the area's dependence on surface water during years of drought. This or any other alternative that involves an increase in pumping is potentially limited by water quality problems (e.g. TDS, salinity). Although the modest increases in pumpage included here are probably acceptable (Belitz and Phillips, 1995), additional

work would be required to determine the long-term impact of such changes on water quality.

A linear optimization model was constructed to predict the maximum potential ground water pumpage from each subarea above the predicted water demands for the next 30 years. Although perfect foresight limits the implementation of the optimization model in practice, the model indicates that ground water supplies of certain subareas in the eastern portion of the study area can be operated far above the target demand rates without leading to inelastic compaction. In contrast, little increase in ground water withdrawal is possible for subareas on the western side.

There are at least three areas in which further work could improve the quality of the model. First, the thickness of the layer representing the interbeds was assumed to be uniform across the study area. Additional field data regarding the composition of the confined aquifer may allow for a better estimation of the spatial distribution of interbed thickness. Second, the model only considers yearly stress periods. Some detail is lost as pumping is averaged over the entire year. A seasonal or monthly model may capture more accurately the ground water fluctuations leading to subsidence. Finally, the time delay of compaction was adequately captured using the IBSI package by sub-dividing the compressible layers. However, equally valid and numerically more efficient results may also be attainable using a package which analytically considers time delay, such as the IDP package (Shearer and Kitching, 1994).

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